HYDROSTATIC LEVELING SYSTEMS*

Pierre F. Pellissier

Lawrence Radiation Laboratory
University of California
Berkeley, California

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Summary

The 200-BeV proton synchrotron being proposed by the Lawrence Radiation Laboratory is about 1 mile in diameter. The tolerance for accuracy in vertical placement of magnets is ±0.002 inches. Because conventional high-precision optical leveling to this accuracy is very time consuming, an alternative method using an extended mercury-filled system has been developed at LRL. This permanently installed reference system is expected to be accurate within ±0.001 in. across the 1-mile diameter machine.

Review of Commercial Devices

There are two fundamental types of hydrostatic leveling systems in use today. The first most common type is based on the bubble level. In this type of level, a small tube is partially filled with liquid and sealed, so that a bubble is included.

When care is taken to suppress thermal gradients in the liquid with a massive metal housing, the surface of the liquid is accurately level. The bubble–in conjunction with an accurately curved ground-glass cover–serves as a precise indicator of the location of the liquid surface. This reference-level surface can be extended mechanically (as in the carpenter's level) with string (as in a line level) or optically, using optical systems of modest or highly refined types, depending on the requirements. The highest precision in the art of optical leveling has probably been attained at BNL and CERN where careful work in solitude, in air conditioned tunnels, yields closures of about 0.010 in./mile. Two weeks or more would be required for a single optical leveling traverse of the 200-BeV machine. During the survey, no other work could be done in the portions of the tunnel occupied by the leveling party. The time required for optical leveling makes it unattractive for the 200-BeV machine.

The second basic type of hydrostatic leveling system is available commercially in two forms. The first of these is the garden-hose type of water-filled, extended hydrostatic level. In this type of level two or more surfaces are connected by tubing or hose. In practice, this simple level, visually read, is accurate to ±1/32 in. in 100 ft, when used with moderate care. The second commercial type of water-tube level uses a micrometer dipper for measuring the level and is accurate to ±0.002 in. in 50 ft when used with care. (It is worthy of note that "level" at the earth's surface is in practice a fairly smooth curve which deviates from a tangent by 0.003 in. in 100 ft. When leveling by any method one attempts to precisely locate this curved surface.)

Design

The design of an extended hydrostatic level is quite straightforward. The fundamental principle of hydrostatics which applies must be stated quite carefully at the outset: the free surface of a liquid–or surfaces, if interconnected by liquid-filled tubes–will lie on a gravitational equipotential if all forces and gradients except gravity are excluded from the system. The forces and gradients that may disturb an extended well-and-tube system are:

1. Air-pressure gradients
2. Surface tension
3. Temperature gradients
4. Flow gradients
5. Vapor pressure
6. Tides.

While the effect of these forces can be calculated, inspection disposes of some of them. Air-pressure gradients in air conditioned spaces are measured in inches of water with a manometer; clearly the system must be hermetically sealed and provided with sealed air-return lines. The forces of surface tension cause errors in capillaries and small tubes; if measuring wells 2 in. in diameter or larger are used, these errors will be negligible. The vapor pressure of water at room temperature can be quite troublesome if thermal gradients exist, because a distilling system results. A difference of 0.1°C between two parts of the system yields a vapor-pressure difference of approximately 0.004 in. to act as the driving force for a still. The gradients due to mass flow will cause an error. Thus it seems safest to exclude water or other liquids with high vapor pressure.

The thermal effects in a practical system are of two types. The first occurs when the system, in equilibrium, is uniformly warmed or cooled. The difference in the coefficients of thermal expansion of the liquid and its enclosure, the tubes, causes a change in the apparent volume of liquid in the system (analogous to the change in bubble size with temperature in bubble levels). No error results from this effect, only an equal change in level in all measuring wells. This effect can be eliminated by choosing tubing with a volume thermal expansion coefficient equal to that of the

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liquid. (Lexan is a very close match for mercury.)

The second type of thermal effect is due to the existence of a thermal gradient across the system. This thermal gradient causes a density gradient in the liquid.

Since the level in each well is determined by a hydrostatic or mass balance among all wells, an increased temperature in one well causes a decreased density of liquid and thus a higher liquid level with no corresponding flow. This error, with mercury as the liquid, is 7×10^{-5} in. per in. of depth per degree centigrade. This error, for oils and other low-vapor-pressure liquids is about five times higher than for mercury. It is obvious that the thermal errors can be acceptably low if the liquid depth is small and vertical tubing runs are avoided. In practice, the overall depth can be held to 1/2 in. or less without difficulty. This would ensure a residual system error of ≈ 0.00035 in. even with 10°C gradients across the system. In precise work the thermal coefficient of the measuring well must be determined in an oven and used to correct readings. With care in design, the measuring-well error can be made negligible.

The probable maximum effect of tides on the system can be easily calculated. The daily earth tide has an amplitude of about 1 ft. The slope of this tide wave will be about 0.004 in./mile. The leveling system lies on an equipotential of gravity. This equipotential moves with the earth and thus the system may not actually respond to the earth tide. Other tidal effects in coastal regions are due to two primary causes. In the first, the ocean tides deform the continental shelf. In the second, the lens of ocean water exerts a gravitational force on the liquid-filled system. In our experiments with a 90-ft-long system in Berkeley, no tidal effects as large as 0.0001 in. in 90 ft are apparent. The system for the proposed AGS will be subdivided into 600-ft lengths, partly to decrease the response time and partly as insurance against tidal effects that might appear in a large system. In any event none of the tidal effects above are significant as far as machine operation is concerned.

To detect precisely the location of a mercury surface, a micrometer head with a hardened steel or tungsten ball tip approximately 0.040 in. in diameter is fitted to the top of the measuring well. An ohmmeter on the high-resistance range (12 V or more and a fraction of a milliampere) is used to measure contact with the surface. This contact is repeatably accurate within ±0.0001 in. or less.

For remote reading of the mercury surface a photoelectric device has been developed with an accuracy and repeatability of 0.0001 in. or less, but for the AGS a capacitance, inductance, or eddy current device that is not sensitive to radiation must be used. Many commercial devices are available. Experience over nearly a year with floats indicates an uncertainty in readings due to sticking, and to condensation of mercury on the float, which changes its floating level by several thousandths of an inch. Due to these uncertainties, no floats will be used in future work.

Tubes of various plastics, about 1/8 in. in diameter have been used in most work. This tube is easily filled, because the mercury meniscus pushes air out ahead of it. Larger tubes are more difficult to fill because air is trapped in the line. The time constant of a system with two 2-in. measuring wells connected by a 0.100-in. tube 100 ft long is 5 min. This system is slightly over-damped. A number of systems using different materials, tube sizes, and lengths have been built, all of which behave normally.

Conclusion

Hydrostatic leveling systems can be quite easily designed and built. Manually read systems of various types in lengths to 100 ft have been built that are stable and dependable. A recording system 90 ft long installed in Berkeley has shown no tidal disturbances as large as 0.0001 inch. A similar hydrostatic system 1000 ft long will be constructed in the Bay Area this year, and experience gained will be applied to the final design of the level reference for the 200-BeV AGS.